AFRL-VS-TR-2002-1593

Global Ionospheric Structure, Dynamics, and System Effects

Robert C. Livingston

SRI International
333 Ravenswood Avenue
Menlo Park, CA 94025

24 June 2002

Final Report

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED.

AIR FORCE RESEARCH LABORATORY
Space Vehicles Directorate
29 Randolph Rd
AIR FORCE MATERIEL COMMAND
Hanscom AFB, MA 01731-3010

This technical report has been reviewed and is approved for publication.

TODD R. PEDERSEN
Contract Manager

GREGORY P. GINET
Chief, Space Weather Center of Excellence

Qualified requestors may obtain additional copies form the Defense Technical Information Center (DTIC). All other requests shall be referred to AFRL/VSBXI.

If your address has changed, if you with to be removed from the mailing list, or if the addressee is no longer employed by your organization, please notify AFRL/VSIM, 29 Randolph Rd., Hanscom AFB, MA 01731-3010. This will assist us in maintaining a current mailing list.

Do not return copies of this report unless contractual obligations or notices on a specific document require that it be returned. Destroy by any means that will prevent disclosure of the contents or reconstruction of the document.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
24 June 2002	Scientific, Final	14 Sep 1992-31 Dec 1999

4. TITLE AND SUBTITLE
Global Ionospheric Structure, Dynamics, and System Effects

5a. CONTRACT NUMBER
F19628-92-C-0179

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)
Robert C. Livingston

5d. PROJECT NUMBER
2310

5e. TASK NUMBER
GH

5f. WORK UNIT NUMBER
AC

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
SRI International
333 Ravenswood Avenue
Menlo Park, CA 94025

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory/VSBXI
29 Randolph Road
Hanscom AFB, MA 01731-2010

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-VS-TR-2002-1593

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
SRI International provided radio and radar support for a number of government programs, especially investigations of the effects of the earth's ionosphere on Air Force systems. Investigations at equatorial, mid, and polar latitudes were carried out using a variety of optical, radar, and radio instruments. A network of ground-based scintillation receivers was established to provide real-time diagnostics and communication outage alerts and forecasts. Barium releases and resulting striation structures (or lack of) were observed with scintillation receivers and HF radar. Ionospheric corrections for GPS tracking of re-entry vehicles were performed for the equatorial ionosphere, and a number of auroral ionosphere experiments were carried out at Sondrestromfjord, Greenland. A scintillation diagnostic array was designed for the HAARP program. Various GPS sensor calibrations and signal analyses were performed.

15. SUBJECT TERMS
Equatorial scintillation   High-latitude ionosphere   Ionospheric heating   Ionospheric effects

Global positioning system (GPS)   Incoherent scatter radar   HF radar

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	19b. TELEPHONE NUMBER *(Include area code)*
UNCL	UNCL	UNCL	UNL		Todd Pedersen	(781) 377-2845

CONTENTS

1 INTRODUCTION

Under this contract, SRI International (SRI) provided radio and radar support for a number of government programs. Primarily, these programs were concerned with the effect of the Earth's ionosphere on Air Force systems, although the contract vehicle was also used to support a number of programs in other radar technology applications.

The ionosphere is a dynamic region, driven at the largest scales by the solar cycle and planetary-scale neutral motions. This background ionosphere is also perturbed by smaller-scale processes, such as gravity waves and instabilities, resulting in a spectrum of electron density structure from large through small spatial wavelengths. The neutral atmosphere dynamics and the configuration of the terrestrial magnetic field affect these processes, to create different ionospheric behaviors at different latitudes.

The scope of the collaborative research between Air Force Research Laboratory (AFRL) and SRI supported under this contract includes work at all latitudes and takes advantage of a variety of optical, radar, and radio instruments. Optical imagers and ionosondes characterize the large-scale background ionosphere, while radio wave scintillation determines the formation and behavior of intermediate-scale irregularities. Incoherent scatter and high frequency radars provide spatial information for both large and small irregularity scales. The collaborative analysis of data from such complementary instruments is much of the reason that significant progress has been made toward an understanding of ionospheric behavior in the past decade.

This report briefly summarizes the ionosphere programs that were supported under Contract F19628-92-C-0179.

2 EQUATORIAL SCINTILLATION

AFRL SCINTILLATION MONITORING NETWORK

The Air Force Research Laboratory at Hanscom, AFB, initiated the Scintillation Network Decision Aid (SCINDA) program in the early 1990's as a means to specify and predict degradation of satellite communication and positioning links caused by ionospheric scintillation in the equatorial region. The concept was to provide a network of scintillation monitoring receivers that would provide scintillation diagnostics in real time, to a global communication outage forecast and alert system.

Ionospheric disturbances can cause rapid phase and amplitude fluctuations of satellite signals observed at or near the Earth's surface. The most intense natural scintillation events occur during nighttime hours within 20° of the earth's magnetic equator, a region encompassing more than one-third of the surface of the Earth. Scintillation affects radio signals up to a few thousand MHz in frequency and can potentially degrade satellite-based navigation and communication systems. SCINDA was designed to provide regional specification and short-term forecasts of scintillation activity to users in real time.

The SCINDA sensor system comprises a multichannel receiver system that collects data and computes scintillation conditions in real time. Those conditions are characterized by the statistical behavior of the signals, and their spatial decorrelation, from which ionospheric drift can be inferred. This information, computed every few minutes, is linked to a data server computer that, in turn, sends the data over the Internet to the SCINDA outage prediction system.

The initial "production" SCINDA system was developed by SRI under this contract and was installed at Antofagasta, Chile, in 1992 at the Universidad Catolica del Norte. That system was initially referred to as the Real Time Scintillation Warning System (RSWS). From Antofagasta, signals from three different geostationary satellites are used: One source at 250 MHz to the west observes the scintillation conditions "upstream", a second 250 MHz source over the South American continent determines "downstream" conditions, and an L-band source near overhead characterizes the severity of effects during strong scintillation.

The system consists of a commercial off-the-shelf (COTS) VXI system, within which there is a managing computer, four COTS high-frequency receivers, and SRI-developed signal down converters and interconnect modules. The VXI standard provides high-speed data transfers and message/interrupt control of the receivers.

The RSWS computer is a standard 486-type CPU modified for use as a VXI controller. In addition to standard DOS/Windows software, it manages the high-speed data bus and interrupt/message control of the VXI system. Receivers 1 and 2 are tuned to channel 4 (244.165 MHz) of the FLTSAT7 satellite at 100° W longitude. The antennas for these receivers are vertically directed; the receiver 1 antenna is on the roof of one building, and the antenna for receiver 2 is on the roof of another building to the east. The baseline between the two antennas has a magnetic east-west separation of 152 meters (determined from the campus map) that is well suited for equatorial drift measurements.

Receiver 3 is tuned to channel 4 (244.065 MHz) of the FLTSAT8 satellite at 23° W longitude. The antenna for receiver 3 is mounted on the roof of the main building and is steered to the azimuth and elevation of the source (azimuth 70°, elevation 31°).

Receiver 4 receives an L-band signal (1544.5 MHz) from the GOES8 satellite at 75° W longitude. The antenna for receiver 4 is a 3-meter dish antenna that is steered toward the satellite (azimuth 348°, elevation 62°) from the roof of the main building.

There are two block down converter modules, one for the three UHF signals and one for L-band. These local oscillators in the down converters are tuned from the system computer during data collection, and output a signal in the high frequency (HF) range (2 to 30 MHz) that is passed to the four WJ receivers.

On power up, the RSWS boots into a fully operational mode. The function of the system is then under the control of (1) a schedule file on the server computer, (2) specific control flags placed on the server by a remote operator, or (3) selected manual keyboard commands. In normal operations, the schedule will be the primary means of control, with the remote commands used for special data collection and diagnostic functions. As

an unattended system, the keyboard commands will be used only during development and diagnostics.

When the data collection first starts, the program checks the operational schedule on the LINIX server to determine whether the current time is within a data collection window. If the time is within the scheduled window, data collection is started; if not, the program checks the server for the presence of a remote control command file that includes operational instructions. If no control file is found, the program recycles through the schedule/remote control check process every 15 seconds. During this looping, the system can also be controlled using particular keyboard inputs.

Once data collection begins, the system will continue to operate until the end time indicated in the schedule is reached. The system then returns to a wait state, looping periodically to check the contents of the schedule file, the presence of a remote control flag, or a keyboard hit.

The RSWS data collection software continuously logs events in a file located on both its local disc and on the LINIX server. Most of the information in the file is routine (such as file numbers and scheduled starts). However, potential system problems are also identified. An example is a warning message if the signal level from a previously functioning receiver and antenna falls below a specified threshold, indicating (most likely) an antenna failure. Dual copies of the report are kept on the two computers to allow identification of network problems between RSWS and the LINIX server (these obviously cannot be recorded on the server if the net is down).

The RSWS at Antofagasta has proven to be extremely reliable and continues to operate after 10 years of routine use. It has also set the pattern for networking formats and general operational logistics to the now much-expanded SCINDA system. The data from the system have been reported in a number of journal articles, a representative paper being *Groves et al., 1997* [1].

3 MIDLATITUDE IONOSPHERIC DYNAMICS

3.1 BARIUM ROCKET RELEASES AT ARECIBO

The CRRES (Combined Release and Radiation Effects Satellite) experiments included a sequence of rocket-launched chemical releases in Puerto Rico. Those experiments in June– July 1992, provided an opportunity to observe the dynamics and evolution of high-altitude chemical releases at middle latitudes. Barium charges were released under both ambient conditions, and into an ionosphere modified by HF heating, and the effects were observed using a number of ground-based instruments. These instruments included backscatter radars, incoherent scatter radar, and airborne scintillation receivers. The periods of heating prior to the rocket release flights provided an opportunity to study heating effects, per se, in the local morning ionosphere, using these same instruments.

SRI participated in the work with instruments that were supporting CRRES: ion-line observations made by the Arecibo incoherent scatter radar, HF backscatter characterization of the ambient ionosphere and tracking of the chemical cloud using the

SRI frequency agile radar (FAR) [2], and transionospheric scintillation characterization of large-scale structure produced by heating and the payload releases made from the AFRL Airborne Ionosphere Laboratory. The barium cloud did not striate, for a reason now well understood, so the initial transionospheric scintillation analysis was adequate. However, more detailed analysis of the incoherent scatter and HF radar continued under this contract.

3.2 ION-LINE RADAR MEASUREMENTS

During the CRRES releases, the Arecibo radar was operating in a plasma-line mode to study the chemistry of the heated barium. In this mode, it was not possible to obtain real-time ion line estimates of ionospheric drift and electron density from the Arecibo radar data collection system. That background information was important, however, to determine suitable launch conditions, and without ion line observations there was no Doppler capability from which to estimate the motion of the cloud after release. Hence, the primary purpose of the SRI incoherent scatter ion line observations at Arecibo was to provide precise measurement of ionospheric electric fields prior to rocket launch.

To provide real-time ion-line data, SRI installed a compact data acquisition system to be used with the Arecibo radar for Doppler processing of one portion of the radar return signal. The components of the system are the same as are used for primary incoherent scatter data collection at the National Science Foundation (NSF) Sondre Stromfjord, Greenland, and ALTAIR, Kwajalein, radars. A second computer provided real-time displays of the ion-line data, including resolved drift vectors.

The Arecibo ion-line observations, while difficult to implement technically, were highly successful. In fact, after the completion of CRRES, the importance of the coincident plasma-line and ion-line observations was recognized, and was implemented as a routine Arecibo operating mode.

3.3 HF RADAR OBSERVATIONS

SRI fielded its FAR system for CRRES for the purposes of

- characterizing the striation images in the lower ionosphere from coherent (perpendicular to B) returns at multiple frequencies,
- obtaining coherent returns directly from the cloud using refractive bending, and
- providing estimates of the ion cloud position after it had drifted out of the Arecibo radar beam.

Because of its frequency and waveform agility, the FAR was an ideal system for use at CRRES. The FAR was installed some distance from the Arecibo radar and operated using both ionosonde and pulse-to-pulse modes, over a frequency range of 6 MHz to about 15 MHz. Because the barium cloud did not striate, image formation in the lower ionosphere did not occur. Otherwise, the FAR results showed its success in identifying structure development and long-term tracking of the drifting ion cloud.

The focus of the continued analysis of the CRRES data under this contract has been on the FAR Doppler maps, which clearly show that scattering did occur, despite the lack of intermediate scale (>100 m) striations. The scattering was unexpected and was initially thought to be due to either coherent returns from small-scale structure in the cloud, or from multiple-path scattering from electron density gradients at the cloud edges. Coincident observations from the incoherent-scatter radar and airborne scintillation receiver suggest that the gradient explanation is unlikely, so a more detailed analysis of the cloud physics was undertaken. The combination of velocity structure seen by the incoherent scatter radar, and the large Doppler shifts of HF returns are likely associated with the observed small-scale scatter. Although schedule demands precluded additional study of the data under this contract, they are observations that warrant eventual publication.

4 EQUATORIAL IONOSPHERIC DYNAMICS

ERIS/FTV RE-ENTRY MISSION SUPPORT

Of fundamental importance to the success of missile defense development programs, such as ERIS and FTV, was the accurate measurement of position and velocity of the target and intercept vehicles. To achieve this measurement accuracy, the ERIS and FTV programs used ranging information from the Global Positioning System (GPS) satellite constellation. During the mission flights, the signals from several GPS satellites were received aboard the target and interceptor vehicles, translated in frequency, and transmitted to a ground-based Translator Processing System (TPS). The GPS range and range-rate for each vehicle-satellite combination were then used by the TPS to resolve the positions and velocities of the two vehicles in real time.

If it were not for the Earth's ionosphere, the type of single-frequency GPS ranging used for ERIS would be highly accurate: only the statistical variations associated with minor system noise would contribute to the vehicle position and velocity errors. However, during the ERIS experiments all GPS signals passed through the dispersive plasma of the ionosphere during the most critical portions of the flights. The ionosphere delays these signals in time proportional to the total electron content (TEC) encountered along the path. The result is that each line of sight from a vehicle to a GPS satellite will have a deterministic ionospheric range error in addition to the small statistical system errors. Depending on the state of the ionosphere and the geometry of the signal path, the ionospheric range error can become as large as hundreds of feet.

GPS range offsets due to the ionosphere are not a problem, per se, if they are nearly the same along all signal paths used in a position solution. However, the geographical location and the local time of the test flights made the ionospheric error effect more complex for ERIS. The Kwajalein Missile Range is located in a region of ionospheric extremes because of its proximity to the magnetic equator. Ionospheric plasma is transported from the equator northward and southward to create an uneven distribution of ionization electron density in latitude during the day. Furthermore, the ERIS experiments occurred near dawn when north–south aligned electron density gradients form at the

sunrise terminator. Thus, the ERIS system had to contend with a complex ionospheric configuration that created a variety of range offsets along its multiple GPS signal paths.

Because ERIS also required precise velocity solutions for the target and interceptor vehicles, the system was significantly affected by the vertical distribution of plasma in the ionosphere. The vehicle velocities were resolved from individual range-rate measurements between the vehicle and the GPS satellites used in the position solution. If the TEC was constant along any signal path, there would be no ionospheric contribution to range-rate error. However, during the ERIS target reentry, the TEC changed rapidly along most of the signal paths, inducing a significant ionospheric contribution to the measured range-rate.

Since single-frequency GPS solutions provide no capability to mitigate ionospheric effects from range and range-rate measurements, it was necessary to predict those errors for ERIS. In particular, it was a mission requirement that the ionospheric errors be estimated just prior to the mission in order to establish the suitability of ionospheric conditions for launch. This required a model that accurately describes the long-term, mean electron density distribution at Kwajalein, and a means to provide short-term information to update the model to account for day-to-day variability.

Short-term ionospheric information at Kwajalein can be provided by the ALTAIR radar, a VHF/UHF system used primarily for reentry missions and space surveillance. It uses a 150 foot steerable dish antenna, and because of its high effective radiated power and receive sensitivity, ALTAIR can also be used in what is referred to as an incoherent scatter mode. The thermal motion of electrons in the ionosphere will scatter back some very small portion of a radar signal from fluctuations in the dielectric constant of the plasma when ions and electrons interact. The radar receives a weak signal from this ion backscatter (approximately 70 dB below that from a moderate-sized satellite). The Doppler-spread spectrum of the received signal can be measured, and from it, the electron/ion density can be determined.

The adapted ionospheric model proved to be an effective means to predict ionospheric position and velocity errors during the multiple reentry missions of the ERIS program. When observational updates were applied, the prediction accuracy achieved for position was approximately 10 ft, and that for velocity was better than 0.3 ft/sec.

Some years after the conclusion of the ERIS program, a follow-on program, designated FTV, initiated tests involving Kwajalein and the ALTAIR radar. By that time, the SRI-built Doppler processor at ALTAIR had been replaced by an in-house measurement system. The operating protocols and ionospheric evaluation established by ERIS were continued, although less detailed characterizations of the ionosphere were obtained. The SRI involvement in these ionospheric measurements was limited to verification that the observed data were consistent with incoherent scatter returns. The ALTAIR incoherent scatter mode was optimized based on the SRI analysis of data from the first two FTV tests.

Although the ionospheric involvement in FTV was small, SRI supported the GPS instrumentation aspects of FTV throughout the program. That work, performed by the Systems Development Division at SRI, has been reported through the NMD program offices in Huntsville.

5 HIGH LATITUDE IONOSPHERIC PROCESSES

5.1 SONDRE STROMFJORD, GREENLAND OBSERVATORY

AFRL and SRI have collaborated for many years in the study of ionospheric processes, through modeling, experiment, and analysis. There has been significant progress made toward an understanding of the origin and nature of ionospheric plasma structure, not in small part because of this association. A portion of the work supported by this contract focused on studies of plasma regimes at polar latitudes. This work used complementary data from optical, incoherent scatter radar, high-frequency radar, GPS ranging, and radio wave scintillation diagnostics to study regimes from large-scale processes through irregularity structure.

A facility that was very important to the AFRL/SRI collaboration is the NSF incoherent scatter radar located in Sondre Stromfjord, Greenland. Although NSF pays for the operating costs of the radar, this contract maintained support of AFRL instruments at Sondre Stromfjord, as well as ensuring campaign support over several years.

The Sondre Stromfjord Observatory is located near the statistical southern boundary of the polar cap, where solar activity and the state of the interplanetary magnetic field (IMF) dominate ionospheric behavior. As such, it sees both auroral and polar cap type ionospheres, and the dynamic boundary that separates the two.

There are states of the IMF during which high electron density patches from lower latitudes are convectively drawn into the polar cap. As they pass across the polar cap, these patches structure, and can produce strong scintillation on VHF/UHF radio paths. The severity of the scintillation is strongly a function of the F-region electron density, and thus, is worst under solar maximum conditions. The study of patches was one of particular interest to the AFRL/SRI collaboration, because of their impact on transionospheric communication systems. The patch campaigns supported under this contract typically involved coincident optical observations from Thule, Greenland, as well as scintillation and irregularity drift measurements from Thule, Qaanaaq, and Sondre Stromfjord instruments.

Another aspect of continued AFRL study is the formation of sun-aligned arcs that occur in the polar cap F region when the IMF direction is reversed. Aligned along the noon-midnight direction, the arcs have a moderately high peak electron density, and rapidly structure as a result of currents or velocity turbulence at their boundaries.

The collaborative work at Sondre Stromfjord has led to an improved understanding of the plasma structure associated with large-scale polar cap patches and sun-aligned arcs (in the polar cap), as well as large-scale plasma "blobs" that form near the auroral boundary. This was achieved through the work of several individuals using a combination of AFRL optical

systems and the incoherent scatter radar. During the time that this contract was under way, an upgrade of the real-time analysis and display capabilities at the Sondre Stromfjord radar was completed. The AFRL campaigns were an opportunity to develop new operating protocols that took advantage of those tools, in particular, making links between optical instruments and the radar. An example is the so-called RODEO mode, which allowed detailed radar measurement of the dynamics within auroral and polar cap arcs, and has become a standard research mode at the radar. Other radar waveform and antenna steering protocols were also developed during this period, many driven by the needs of the AFRL research.

Among the scientific papers resulting from the collaborations supported under this contract are the following:

Basu, S., S. Basu, R. Eastes, R.E. Huffman, R.E. Daniell, P.K. Chaturvedi, C.E. Valladares, and R.C. Livingston, "Remote Sensing of Auroral E Region Plasma Structures by Radio, Radar, and UV Techniques at Solar Minimum," *J. Geophys. Res.*, Vol. 98, No. A2, pp. 1589-1602, February 1, 1993.

Doe, R.A., M. Mendillo, J.F. Vickrey, L.J. Zanetti, and R.W. Eastes, "Observations of Nightside Auroral Cavities," *J. Geophys. Res.*, Vol. 98, No. A1, pp. 293-310, January 1, 1993.

Gallagher, H.A., E.J. Weber, J.F. Vickrey, and R.L. Carovillano, "Plasma Flows Associated with an Auroral Arc at the Polar Cap Boundary," in *Auroral Plasma Dynamics, Geophys. Monogr. Ser.*, edited by R.L. Lysak, Vol. 80, pp. 81-88, AGU, Washington, D.C., 1993.

Another aspect of the research funded under this contract was the continued, low-level support of the variety of AFRL instruments maintained at Sondre Stromfjord. These are the systems that operate continuously, collecting synoptic data for the use of any radar users. Although that support is not always specifically acknowledged, it is important, and has contributed to the following papers, plus many more:

Doe, R. A., J. F. Vickrey, E. J. Weber, H. A. Gallagher, and S. B. Mende, "Ground-based signatures for the nightside polar cap boundary," *J. Geophys. Res.*, 102, p. 19,989, 1997.

Doe, R.A., J.F. Vickrey, and M. Mendillo, "Electrodynamic Model for the Formation of Auroral Ionospheric Cavities," *J. Geophys. Res.*, Vol. 100, p. 9683, 1995.

Basu, S., S. Basu, P.K. Chaturvedi, and C.M. Bryant, Jr., "Irregularity Structures in the Cusp/Cleft and Polar Cap Regions," *Radio Sci.*, Vol. 29, No. 1, pp. 195-207, Jan-Feb 1994.

Berg, G.A., M.C. Kelley, M. Mendillo, R.A. Doe, F. Primdahl, C. Kletzing, J.F. Vickrey, and K.D. Baker, "Formation and eruption of sun-aligned polar cap arcs," *J. Geophys. Res.*, Vol 99, No. A9, pp. 17,577-17,589, September 1994

Doe, R.A., M. Mendillo, J.F. Vickrey, J.M. Ruohoniemi, R.A. Greenwald, "Coordinated Convection Measurements in the Vicinity of Auroral Cavities," *Radio Sci.*, Vol. 29, No. 1, pp. 293-309, Jan-Feb 1994.

Valladares, C.E., S. Basu, J. Buchau, and E. Friis-Christensen, "Experimental Evidence for the Formation and Entry of Patches into the Polar Cap," *Radio Sci.*, Vol. 29, No. 1, pp. 167-194, Jan-Feb 1994.

5.2 IONOSPHERIC HEATING

HAARP Scintillation Diagnostic

The High Altitude Atmospheric Research Program (HAARP) site at Gakona, Alaska, has evolved into a major scientific research facility. Although its primary instrument is the HF ionospheric heater, many ionospheric diagnostics are associated with the facility. The HAARP VHF Diagnostic Satellite Scintillation (SATSIN) system is used to characterize the structure and dynamics of plasma irregularities created during HF heating of the upper atmosphere. It does this by measuring, in time and space, the weak to moderate transionospheric phase and amplitude scintillation at VHF and UHF. Such irregularities are a near-constant feature of the natural auroral zone, but can also be created by energy transmitted from the high-power HAARP array. Irregularities are produced by HAARP when its high-frequency radio energy is converted to heat in the ionosphere, by a thermal self-focusing instability at the altitude where the heating signal frequency matches the plasma frequency of the electron density profile. The cross-magnetic field dimension of these irregularities depends on many factors, but it is typically of a few hundred meters.

The SATSIN system characterizes plasma irregularities by the effect those irregularities have on a radio signal. The system receives VHF radio transmissions from a high satellite through the ionospheric volume that is being measured. If naturally occurring or heater-generated plasma irregularities are intercepted, they perturb the radio signal slightly as it passes through, and SATSIN measures these "scintillation" effects.

The system hardware consists of a high-performance eight-channel antenna/receiver system and two networks. Up to eight helix antennas are distributed in an array over an area about 500 ft by 1000 ft in order to measure small spatial changes in the received signal. The scientific parameters derived from the SATSIN system provide an accurate and extensive characterization of the plasma irregularities. The amount of signal perturbation observed can be related to the strength of the irregularities. The frequency spectrum of the data time series indicates the size of the irregularities, and how they evolve in time. Finally, correlation analysis of the signals received over the antenna array can estimate the shape and movement of the plasma structure.

Under this contract, the SATSIN system was first installed in Norway for participation in an HF heating campaign at the EISCAT site near Tromso. The full eight-receiver system was operated from Grunnfjord, approximately 100 km north of the EISCAT heating facility, to place the VHF propagation raypath to the beacon satellites directly above the heater at an altitude of 250 km. The antenna array consisted of eight helix units, placed in an area approximately 400 m by 200 m, in a pattern optimized for anisotropy observations.

Several days of data were collected, under a variety of geophysical conditions. During the magnetically quietest of these periods, cycling of the heater produced corresponding rapid onsets of scintillation. However, the magnitude of the propagation effects from period to period were quite different, which is thought to be a result of a changing F-region layer altitude and electron density. At the local time during which the observations were made, the F layer typically starts to drop, with a corresponding decay in peak electron density. A summary of the observations, with a focus on the irregularity formation process estimated from the scintillation signal spectra, have been published by Basu et al. [3]. It was also observed (but not quantitatively proved) that during periods with significant naturally occurring irregularities, there may be some suppression of the irregularity structure; this is an effect that has been theoretically predicted, but not yet measured. Also clear from the data is the importance of background plasma drift that can move the long-lifetime intermediate scale structure in and out of the scintillation raypath.

Following the Norway experiments, the SATSIN was operated at SRI while an extensive graphical user interface (GUI) was being developed. The intent of the interface, developed under the Unix X Windows system using a development tool called U/IMX, was instrument control, hardware diagnosis, real-time data display, and archive data review and display. The GUI was to function as both a local user interface and the networking of data to the HAARP Diagnostics Control Center (HDCC). Although it had many nice features and elegant displays, the GUI was quite complex, and as the needs of the HDCC developed, it became clear that it was less adaptable than planned. Perhaps most important, licensing agreement for the costly U/IMX tool would preclude any routine programming changes in the field. Hence, that development was dropped and a more realistic GUI was started, using Open Source tools under the Linux operating system.

In 1995, SATSIN was installed at the HAARP site in Gakona, Alaska. This was an interim installation during which the initial networking to the HDCC and data display formatting were to be established. During this period, an interesting archive of naturally occurring scintillation was collected, although the on-site location precluded observation of heater-generated irregularities.

After some months at HAARP, the search for a permanent SATSIN site was made. As a thermal self-focusing scintillation diagnostic, the radio path between SATSIN and the satellite beacon should pass directly over HAARP at an altitude of about 250 km. Since the satellites over the Pacific provide the best propagation geometry for scintillation measurements, a search for a permanent SATSIN site was made of the region to the east of Gakona. It was found that the opportunities are minimal, due to the absence of routine electrical power and the proximity and extent of the Wrangell-St. Elias National Forest and National Park. Eventually, a location at Slana, Alaska, was chosen because it assured continuous power, and the best (if not optimum) propagation geometry: There are a few hours each day during which the geometry of the radio path is usable for heating observations.

Prior to any routine operations at Slana, the SATSIN system was again operated in support of heating experiments at EISCAT in Norway. For this second campaign, the heating effectiveness of the EISCAT was reduced from that in 1992, for a number of reasons. Scintillation observations were made again from Grunnfjord, as in 1992, and also from Nordlenangen to the northeast of EISCAT, which provided even better propagation geometry through the heater beam. Unlike the 1992 experiments, coincident stimulated electromagnetic emission data were collected to determine their effectiveness as a surrogate for transionospheric scintillation. These data are yet to be published.

After the second Norway campaign, the SATSIN system was permanently installed at Slana using the full eight-antenna receive array. Initial campaign observations carried out near the end of this contract produced a surprising result: HAARP was shown to have little or no heating effect, relative to EISCAT. That issue is still outstanding, even after several subsequent campaigns.

SATSIN has now been linked to the HDCC using telephone PPP protocol, and the networking to provide web data displays to HAARP is now established. The automatic operation of a complex system at a remote site with locally generated power has not been smooth, although many of the problems are attributable to the aging technology used in the receiver system. The usefulness of SATSIN as a diagnostic for heating has been illustrated in the Norway campaigns, if not at HAARP.

5.3 IONOSPHERIC EFFECTS ON GPS

5.3.1 GPS W SYSTEM SENSOR CALIBRATION

Satellites in the GPS support a number of missions including the detection and location of atmospheric nuclear detonations. Three sensors are allocated to the nuclear mission: the Y sensor collects optical signatures, the X/D sensor collects radiation signatures, and the W sensor collects electromagnetic signatures. The geolocation capability of the Nuclear Detection System (NDS) depends on precise measurement of the time of arrival of the electromagnetic signature aboard multiple satellites. The precision specified for NDS is so high that it can only be achieved when the signal-to-noise ratio is very large. Three 2 MHz-wide filters separated by approximately 10 MHz are used to sample the received signal in the 110 to 150 MHz frequency band. This requirement for large signals has made it difficult to test the W sensors in orbit, especially to test sensors aboard multiple satellites simultaneously. Attempts were made to determine the location accuracy of NDS using a high-voltage pulser connected to a 150 ft diameter parabolic steerable antenna located at a joint SRI/Stanford University field site at Stanford, California. Four satellites were illuminated sequentially at precise times so that simultaneous illumination could be simulated.

Under a task added to Contract F19628-92-C-0179 by Air Force Space and Missile Systems Center/CZ on 1 November 1993, SRI International was assigned the responsibility to provide the 150 ft antenna, a high voltage feed, and a timing system. Under separate contract, Sandia National Laboratory (SNL) was responsible for providing the high-voltage source and the cable to carry the output to the antenna feed point. In addition, SNL was tasked to analyze data downlinked from the satellites to the

integrated correlation and display system. Responsibility for independent data analysis was assigned to Los Alamos National Laboratory (LANL). LANL also provided technical support to SRI, including use of the Black Beard satellite to measure radiated signal levels. The Air Force Second Satellite Operations Squadron (2SOPS) and the Air Force Technical Applications Center (AFFAC) provided satellite uplink commands and distributed downlink data. Coordination and planning was carried out by ARINC Corporation.

High-level testing of the W sensors was originally scheduled for mid-March 1994.Approximately 36 hours before testing was to begin, the tripod on the 150 ft antenna collapsed and sustained major damage. Repairs were completed by mid-July and four satellites were tested on 9 and 16 October.

The instrumentation established for the W sensor tests consisted of four subsystems: transmitter, timing, data acquisition, and aircraft surveillance.

The transmitter subsystem consisted of a high-voltage pulse generator, a transmission cable, a feed antenna, and the 150 ft parabolic steerable reflector. Together, these components delivered electromagnetic pulses to the GPS satellite that yielded -60 to -65 dBm in 2 MHz bandwidth at the W sensor antenna terminals over the frequency range 110 to 150 MHZ. The levels actually delivered were 10 to 15 dB less than the original goal of -50 dBm.

The timing subsystem consisted of an electromagnetic sensor on the surface of the 150 ft dish, a threshold detector (a digitizer), two GPS receivers, a time interval counter, and a cesium beam reference oscillator. Together, these units measured the time of departure of each pulse relative to the reference point of the 150 ft antenna structure to an accuracy of about ±12 ns. Since multiple satellites could not be tested simultaneously, it was important to measure the absolute time of signal departure very accurately so that multi-satellite collections could be synthesized.

The data acquisition subsystem consisted of a high-speed digitizer and a personal computer. The digitizer recorded the signals observed on the surface of the 150-ft dish and the PC-acquired data from this and other instruments.

The 150 ft diameter antenna facility at Stanford was used successfully in October 1994 to transmit broadband electromagnetic pulses to W sensors on four GPS satellites to test their capability to geolocate nuclear sources. Because the firing times were measured to approximately ±12 ns absolute time, results from sequential testing of satellites can be used to simulate simultaneous testing. The signal levels achieved using the SLS-3 pulse source provided by Advanced Pulse Power Technology were 10 to 15 dB less than the target goal of -50 dBm in 2 MHz bandwidth at the output of the W sensor antenna. A number of modifications are possible that should lead to 10 or even 15 dB enhancement for future tests. These include improving oil management, upgrading or replacing the transmission cable to suppress corona loss, restoring the ferrite section of the pulser to sharpen the rise time and increase the high-frequency components, rebuilding the nonlinear resonant circuit to shift its center frequency to higher frequencies, and adding a tuning stub to balance the bipolar waveform to eliminate DC components. Delivery of the high-voltage signal over 250 ft of RG 220 cable was a major problem that was partially

solved by filling the cable with oil. Despite significant efforts to keep the cable filled with oil, 2 to 6 dB of unnecessary signal loss was experienced during calibration of W sensors on 9 and 16 October. It has already been demonstrated that this loss can be recovered through better oil management of the existing RG 220 cable. It is unlikely, however, that the existing cable can handle the 5 dB additional signal capacity that still remains in reserve in the SLS-3 power source. To unlock this 5 dB reserve, it may be necessary to replace the existing RG 220 with an aluminum-tape-wrapped high-voltage version of RG 220, or with an oil-filled 4-inch heliax cable. The oil-filled heliax cable should be able to handle 500,000 volts peak-to-peak. Restoration of the ferrite section, retuning of the nonlinear cavity, and addition of a tuning stub is expected to shift out-of-band energy into the W band. If this is successful, it may be possible to deliver up to 10 dB more signal in the W band without increasing the peak voltage on the cable. In this case, RG 220 cable may still be able to deliver adequate signal to the feed horn.

5.3.2 GPS TRANSMISSION SIGNAL ANALYSIS

In what was planned to be an extension of the NDS, US Air Force Space and Missile Center (SMC) provided funding for a second calibration test of the GPS nuclear monitoring capability (NCTII) in 1997. In support of that effort, meetings at ARINC (Colorado Springs) were attended at which another topic was brought up regarding support of new GPS launches: the failure of the primary GPS system support dish antenna at Camp Parks, California.

SRI was asked if GPS L-band parameters could be measured from Menlo Park using the 150 ft antenna at Stanford University, which was judged to be feasible. To accelerate the process, it was decided to support the effort using funds already in process for the second W sensor calibration effort. It was agreed that the L-band measurements would begin promptly if SMC could officially reallocate the NTCII funds and add whatever additional funds were needed.

Meetings were held with the Camp Parks facility staff to discuss the GPS transmission measurements and to determine what support SRI could provide. Almost everything at Camp Parks was dependent on a one-of-a-kind receiver that could not be transported for use with the SRI antenna in Menlo Park, because of its condition. However, with the information gained at Camp Parks, SRI and ARINC generated optional approaches to provide the needed measurements to the Air Force. One option was to do as much as possible using available SRI equipment and personnel. Another was to team with Stanford Telecommunications (STel, a GPS system supplier) and to use state-of-the-art hardware to simultaneously measure essentially all the parameters identified by the Air Force. These were defined as the measurement requirements contained in the ARINC test plan for the first Block IIR satellite.

A decision was made by the Air Force to involve STel, and additional funding for the collaboration was supplied. Originally, the partition of responsibility was that SRI would measure the RF related parameters and STel would measure the code-related parameters. On the RF side, a concept was developed to measure each of the multiple signal parameters, and the COTS equipment was assembled to make the measurements. The Air Force schedule required a demonstration of the capability within approximately two

weeks, which was completed, with STel participating using one of its Time Transfer System receivers.

After the successful demonstration and an Air Force decision to proceed, development of the RF measurement system continued at a rapid pace. Regarding the code parameters, STel found that it could not measure a number of code parameters, and therefore wanted to embark on a costly development effort. Without sufficient budget or time for that development, it was decided that SRI would digitize portions of the signals and use processing to extract the desired parameters. The hardware and software were subsequently assembled to control the measurement instruments, and to collect and process the data.

Fortunately, the measurements were delayed several weeks because it took much longer to get the new Block II satellite (SVN 43) into proper orbit and turned on. The first SVN 43 L-band measurements were conducted successfully in mid-August, 1997, and continued on through September. Essentially, every measurement requirement was met, although some measurements, such as code fidelity, were not analyzed to the extent possible.

After September, 1997, follow-on L-band transmission measurements from Stanford continued under support through the Charles Stark Draper Laboratory (CSDL). The formal results obtained under this contract were combined with new results obtained in 1998.

6 REFERENCES

1. K.G. Groves, et. al., "Equatorial scintillation and systems support," *Radio Sci.*, 32, pp. 27227–27247, 1997.
2. R.T. Tsunoda, R.C. Livingston, J.J. Buonocore, and A.V. McKinley, "The frequency-agile radar: A multifunctional approach to remote sensing of the ionosphere," *Radio Sci.*, 30, 1623, 1995.
3. Basu, S., S. Basu, P.K. Chaturvedi, and C.M. Bryant, Jr., "Irregularity Structures in the Cusp/Cleft and Polar Cap Regions," *Radio Sci.,* Vol. 29, No. 1, pp. 195-207, Jan- Feb 1994